METHOD AND SYSTEM FOR SYNCHRONIZING LOCATION FINDING MEASUREMENTS IN A WIRELESS LOCAL AREA NETWORK

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a continuation in part of co-pending United States Patent Application "METHOD AND SYSTEM FOR LOCATION FINDING IN A WIRELESS LOCAL AREA NETWORK", Ser. No. 10/225,267 filed on August 20, 2002, the specification of which is herein incorporated by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to wireless networks, and more specifically, to a method and system for synchronizing a location finding system within a wireless network.

2. Background of the Invention

A multitude of wireless communications systems are in common use today. Mobile telephones, pagers and wireless-connected computing devices such as personal digital assistants (PDAs) and laptop computers provide portable communications at virtually any locality. Wireless local area networks (WLANs) and wireless personal area networks (WPANs) according to the

Institute of Electrical and Electronic Engineers (IEEE) specifications 802.11 (WLAN) (including 802.11a, 802.11b, etc.), 802.15.1 (WPAN) and 802.15.4 (WPAN-LR) also provide wireless interconnection of computing devices and personal communications devices, as well as other devices such as home automation devices.

Within the above-listed networks and wireless networks in general, it is desirable to know the location of devices for operation of location-based services, mapping of network facilities, and security. The above-incorporated parent application describes a method and system for location finding within a wireless network and various applications for the location finding results. The method and system use the time-difference-of-arrival (TDOA) of a transmitted signal received at multiple receivers within a wireless network in order to determine the position of the transmitting device via triangulation.

In the TDOA location finding system described above, synchronization of devices is essential so that accurate TDOA measurements are made between the network devices. Synchronization in the above-referenced parent application is

achieved through synchronizing a timebase in each of the location-finding units.

Hard-wired synchronization schemes may distribute a clock from a central source, but distribution of a clock is a costly alternative to synchronization. Hard-wired schemes that pass synchronization error information over a wired network connection as well as wireless synchronization schemes are preferable, but rely on stability and accuracy of the local clock in each location receiver.

Synchronization of local-clock timebases via a synchronization message consumes valuable network bandwidth and the accuracy of the message-based synchronization scheme described above is dependent on the frequency of synchronization messages. There is an upper limit on the accuracy of the above-described synchronization scheme determined by how frequently synchronization messages can be transmitted and received. Therefore, it would be desirable to provide a method and system for accurately measuring location within a TDOA-based location finding system that introduces little or no synchronization overhead or distribution of a wired high-frequency clock or accurate edge reference signal to the location receivers.

SUMMARY OF THE INVENTION

The above objective of providing a method and system for accurate TDOA-based location finding with little or no synchronization overhead in a wireless network is achieved in a method and system for synchronizing TDOA-based location finding measurements in a wireless local area network.

The method is embodied in a system that gathers time-difference-of-arrival (TDOA) information, for signals transmitted from one or more known transmission locations, from multiple location receivers located at known positions. The differences between the gathered TDOA information and theoretical TDOA values based on known positions of the location receivers and the transmission locations are computed. Synchronization error (e.g., offset and drift between the devices' local timebases) is determined from the differences between the theoretical and gathered TDOA information and then subsequent and/or prior TDOA measurements for locating wireless devices at unknown positions are corrected in conformity with computed synchronization error, compensating for offset and drift in the location receivers' local clocks and also compensating for differences in initial timebase counts of the location receivers.

The TDOA measurement corrections may be made at a particular wireless device such as a master wireless network unit, which may be an access point, or at a separate wired or wireless-connected server that computes the location of other wireless devices in subsequent TDOA location finding measurements. The TOA information from the location receivers is corrected in conformity with offset and frequency drift estimators calculated from the computed differences between the gathered and theoretical TDOA information, and the system can perform backward computation to correct signals already received. Kalman filters may be employed that predict error in the location receiver timebases in conformity with statistics of a TOA difference sample set.

Alternatively, the computed differences may be used to correct the local clocks of the location receivers by sending correction information to the location receivers for compensating the local timebases and/or adjusting the frequency of the local clocks.

The foregoing and other objectives, features, and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiment of the invention, as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a pictorial diagram depicting a wireless network organized in accordance with an embodiment of the present invention.

Figure 2 is a block diagram of a location receiver in accordance with an embodiment of the present invention.

Figure 3 is a block diagram showing further details of the location receiver of **Figure 2**.

Figure 4 is a block diagram of a wireless network in accordance with an embodiment of the present invention.

Figure 5 is a graph depicting calculations within a method and system in accordance with an embodiment of the present invention.

Figure 6 is a flowchart depicting a method and operation of a system in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENT

The above-incorporated U.S. Patent Application "METHOD AND SYSTEM FOR LOCATION FINDING IN A WIRELESS LOCAL AREA NETWORK" details a method and system for providing location finding within a wireless network, such as a WLAN (e.g., IEEE 802.11) or WPAN network, by determining a time-difference-of-arrival (TDOA) profile for signals received from wireless devices connected to or attempting to connect to the wireless network.

The system and method described in the above-incorporated patent application describes location finding using dedicated location receivers having incorporated location finding electronics that can detect an accurate time-of-arrival (TOA) of standard signals within the network, such as beacon signals (broadcast) or handshaking signals. By observing time-of-arrival (TOA) of the signals at multiple units, determining time-difference-of-arrival (TDOA) for the signals, and then triangulating the resulting TDOAs at a location server device the location of a transmitting device can be found.

In TDOA location-finding techniques, the location of a transmitting source is determined by triangulation based on the timing between the signal arrivals at the multiple location

receivers. Precise synchronization of the multiple location receivers is essential in order to produce accurate results, as differences between clock frequencies and timebase counts of the multiple location receivers cause error in the determined location of a transmitting unit.

The present invention provides compensation for location finding error without requiring hard-wired or other physical synchronization of the location receivers. Computation of synchronization error and subsequent correction of TDOA measurements ("virtual" synchronization) may be performed via calculation in software. Alternatively, the computed synchronization error may be used to provide physical synchronization by correcting local clocks and/or setting location receiver local timebase counts, thus providing physical synchronization as opposed to "virtual" synchronization.

Adjustment of the location receivers is not required as long as the device performing the location computations has sufficient information to compensate for frequency drift and offset among the various location receivers, as well as compensate for differences in the initial time readings of the participating wireless devices. Therefore, synchronization within the context of the present invention should be understood

to include both a priori and a posteriori adjustment of the gathered TDOA data (virtual synchronization), as well as a priori adjustment of the timebase used to gather the TDOA data as an alternative physical synchronization scheme.

One manner of accomplishing the above-mentioned compensation is to gather TOA data for pairs of fixed position location receivers receiving a periodically transmitted signal and statistically track changes in the TDOA for the received signals over time. For fixed position location receivers, the changes in TDOA measurements indicate changes due to frequency drift and offset in the local (internal) clocks and constant differences indicate the accumulated timebase count error at the location receivers at the time of an initial measurement. In order to track the absolute error and drift in the TDOA measurements and compensate for them in location-finding results, statistical filters known as Kalman Filters are employed. A Kalman filter is an ideal Gaussian estimator in that the Kalman filter output coefficients, which are determined from sample statistics of the Kalman Filter input data, yield the best mean-square fit to a straight line. The coefficients (slope and offset) of the line are easily updated as new samples are gathered, via the Kalman filter algorithm.

However, in order to process TOA data from a number of location receivers and successfully use all of the TOA data obtained, a number of Kalman Filters equal to the number of pairs (permutations of subset size two) of location receivers must be calculated and continuously updated, incurring a significant computational burden within the system. The present invention provides an additional embodiment in that reduces the number of filters required for virtually synchronizing the location receivers by distributing the computation of synchronization information and associating groups of location receivers within the wireless network.

Referring now to the figures and in particular to **Figure 1**, a wireless network **10** within which the present invention is embodied is depicted in a pictorial diagram. Fixed-position location receivers within the wireless network are associated in groups **12A-C**, although not necessarily all fixed-position location receivers within wireless network **10** will be assigned to any group. Groups **12A-C** are used to reduce the complexity of the TOA measurement and drift/offset compensation for the system by referencing groups to each other via one or more selected receivers in each group. Location receivers **16,14** are associated together and selecting one location receiver as a primary location receiver **14** in each group. Location receivers **16A-D** are

associated with a primary location receiver **14A** within group **12A**. Instead of calculating and tracking TDOA differences between each location receiver **16** in wireless network **10**, the present invention calculates only TDOA differences between primary location receivers **14A-C** and the other location receivers **16A-F** (as well as the other location receivers depicted in the drawing, but not indicated by reference designator). Thus, groups **12A-C** reduce the number of Kalman filters required to track frequency drift and offset of the local clocks within location receivers **16,14**.

Location receivers **16,14** in each group are listed in order of descending preference for use as the primary receiver. Ordering may be arbitrary, or based on a factor such as the physical locations of the location receivers relative to an access point. If the primary receiver does not report a beacon signal TOA, then the secondary receiver's reported beacon signal TOA can be used to estimate the interval between the last beacon signal and the present beacon signal. That difference is then added to the primary receiver's TOA for the previous beacon signal to determine the primary receiver TOA. If neither the primary nor secondary receive report a particular beacon signal, the algorithm proceeds down the list to the tertiary receiver, and so forth. The order of receivers in the list can be made

adaptive and responsive to conditions such as failure to report several consecutive beacon signal TOAs, measured signal quality and so forth.

For multiple group location finding systems, in order to determine the relationship between groups, "mutual" location receivers **16C** and **16E** are associated as members of more than one group. A mutual receiver can be a member of more than one group, providing synchronization of all of the groups in which the mutual receiver is associated. All that is necessary to support synchronization of multiple groups **12** is that each group **12** has at least one location receiver (e.g., location receiver **16C**) synchronized with another group. Since within group **12A**, the clock drift and offset for each location receiver **16A-D** is known with respect to primary location receiver **14A**, the timebase relationship between **14A** and location receiver **14B** can be calculated and similarly the timebase relationship between location receiver **16E** and primary location receiver **14B** permits resolution of the timebase relationship between primary location receivers **14C** and **14B**, which permits calculation of timebase offset and drift for any combination of location receivers **14** and **16**. The other requirement of a multi-group location finding system is that all of the groups be referenced to another group

via a mutual location receiver so that no group is left without reference to the other groups in the wireless network.

In addition to the fixed-position location receivers associated in groups **12** above, wireless network may include mobile (or other stationary) wireless devices **18A** and **18B**. Location of wireless devices **18A** and **18B** can be very accurately determined due the synchronization (virtual or actual) of the location finding system. In general, the location finding ability of wireless network **10** permits detection of mobile or movable device as well as determination of whether or not any fixed device has moved or is being impersonated. In order to determine location according to the system and method of the present invention, devices used as location receivers in the sense that they incorporate the requisite electronics and are participating in the calculation of location of another device, must be in a fixed location and their actual position known, so that the theoretical TDOA relative to another location receiver (due to the propagation time differences) may be calculated and used to adjust the TDOA calculation that determines the location of other devices. Once the TDOA deviation of the locating receivers have been tracked and estimated, the model of drift (due to frequency offset and frequency drift) and bias (initial offset of the timebases) derived from the synchronization method

outlined above can be applied to location determination TDOAs from other wireless devices, including signals received prior to and after a beacon signal.

Referring now to **Figure 2**, a location receiver **20** in accordance with an embodiment of the present invention is depicted in a block diagram. Location receiver **20** may be a dedicated location unit, or may be a wireless network device having enhanced features for location determination according to TOA measurements. A WLAN transmitter/receiver **22A** is coupled to an antenna **21** for receiving wireless network signals, which will generally be direct-sequence spread-spectrum signals (DSSS). Antenna **21** may include multiple antennas coupled to WLAN transmitter/receiver **22A** in order to provide spatial diversity. A DSSS baseband processor **24A** detects and decodes the DSSS signals and passes the decoded information to a media access control (MAC) processor **26A** that generates MAC (layer 3) network packets and passes them to a transmission control protocol/Internet protocol (TCP/IP) interface **28** for conversion to the TCP/IP (layer 4) packets for communication with the network-coupled device. In the return direction, TCP/IP packets received from the network-coupled device at TCP/IP interface **28** are converted to MAC packets by MAC processor **26A** and are passed for encoding (DSSS modulation) to DSSS baseband processor **24A**,

which provides a signal input to the transmit portion of WLAN transmitter/receiver **22A**. WLAN transmitter/receiver **22A** transmits a wireless network signal to other network devices via antenna **21**.

A TOA signal section is provided by a second WLAN transmitter/receiver **22B** (or a single transmitter/receiver can be used for the location section and network section of the location unit as long as the TOA measurement requirements are fulfilled by the receiver design). WLAN transmitter/receiver **22B** receives a signal from antenna **21** and sends it to a special DSSS processor **24B** that determines the TOA of the received signal. The TOA information is passed to a location controller that includes a MAC interface **26B** coupled to MAC processor **26A** in the network section, so that the TOA information can be communicated to a master unit within the wireless network. Alternatively, the communications path from MAC interface **26B** can be passed to a non-wireless Ethernet interface or other wired LAN interface for communicating the TOA information to the master unit.

A clock synthesizer **25** provides the local clock for transmission/reception frequency generation/selection, as well as internal timing of DSSS signal processor **24B**. In practice, clock synthesizer may include multiple clock circuits for

clocking blocks internal to location receiver **20**. Clock generator **25** is coupled to location controller **26B** so that in an alternative embodiment of the present invention, clock generator **25** frequency can be adjusted in conformity with network messages received from a master unit that computes the frequency offset of a clock within clock synthesizer in conformity with the gathered TOA difference information described in general above.

However, in the main, the techniques of the present invention are used to compensate for received time of arrival values by calculation (virtual synchronization) rather than actually adjusting clock generator **25** frequencies. If a hardware frequency adjustment is employed, the adjustable frequency may be the local clock for the entire location receiver **20** (thus adjusting the transmission/reception synthesizer), or may be the frequency of a separate clock within clock generator **25** that clocks only the location-finding electronics of DSSS signal processor **24B**. Adjustment of clock generator **25** is generally performed by programming divisor/multiplier values within a synthesizer forming clock generator **25**, but may also be accomplished by tuning a resonant oscillator, such as in a varactor-tuned crystal oscillator (VTXO) with an associated D/A converter and control electronics as are well known in the art. Once the frequency offset and

drift is compensated, only the timebase offset must be corrected (generally by resetting the timebase counter) or otherwise accounted for in the measurements. However, the above-described hardware adjustments are only necessary for physical synchronization. The virtual synchronization techniques of the present invention do not require hardware adjustment at all. The physical synchronization techniques may be used in combination with the virtual synchronization computation to reduce the range over which the virtual synchronization must correct for error in the location receiver timebases.

Referring now to **Figure 3**, details of DSSS processor **24B** are depicted in a block diagram. The **decode** input accepts signals from a receiver (WLAN transmitter/receiver **22B**) and a PN sequence matched filter **32** correlates the location signal to provides a series of samples in (I,Q) pairs that are stored in a sample buffer **33**. A **Time Slot Start** signal is provided by WLAN transmitter/receiver **22B** and is used to start the sampling process via a timer latch **35**. A timebase **36** provides the reference clock for sampling, and may be synchronized by the adjustment of the clock generator **25** as described above for "physical synchronization" providing the reference signal to timebase **36** in accordance with one embodiment of the invention, alternatively, timebase **36** may be periodically set by location

controller **26** in response to messages received from a master unit via MAC processor **26A**.

In general, timebase **36** does not need to be corrected at all, as computational adjustments to TOA measurements (generally performed in the master unit) correct for variations in clock generator **25** frequency and differences in timebase initial values (virtual synchronization). It should be noted that the precision of timebase **36** can be such that the TOA measurement precision is to a time interval shorter than the length of an individual sequence bit or "chip". In general, the device is capable of determining the arrival to a precision of 1/10 to 1/64 of the sample interval.

A digital signal processor (DSP) **34** computes the TOA of a received signal and transmits the TOA information to the master unit or server (the unit that performs the synchronization computations) over a wired or wireless network. Location controller and MAC interface **26B** sends the TOA information to MAC processor **26A**, which then formats the TOA message and TCP/IP interface **28** sends the TOA message through the wired or wireless network to the master unit. For group-organized systems, the TOA differences between the primary location receiver and each of the other members can be calculated (generally within the

primary location receiver) and the TOA differences for that group communicated to the master unit and the master unit itself may be one of the location receivers, primary or otherwise. Additionally, the reference transmitter in the system may be an access point normally provided in the network, a dedicated beacon unit, one or more of the location receivers, or a device otherwise located in a predetermined position with respect to the location receivers. If location transceivers are used to implement the beacon used for synchronization, the transceiver transmitting the beacon message can be selected so as to reduce multipath error and the designated beacon sending unit can be rotated among the transceivers to further reduce multipath error, as all locations of the location receivers are known.

The beacon transmit interval may also be system programmable in order to achieve the desired location finding accuracy, or based on available bandwidth (more frequent beacon transmissions when the network load is low), et cetera. Multiple beacons and/or multiple antennas coupled to a single beacon and selected via a switch may be employed in order to improve synchronization and location determination accuracy by providing multiple transmit locations. The channel used to transmit beacon messages and beacon power levels can be dynamically adjusted to improve performance, minimize interference between beacons and

avoid interference from other devices. The beacon transmit channel can also be adjusted based on measurements of channel quality as evaluated by the synchronization computations at the master unit, or by determination of other signal quality indicators provided from the location receivers or as detected at the master unit. Alternatively multiple beacons may rotate through a set of multiple transmission channels and the receivers may either selectively receive one or more of said multiple channels, or the receivers may frequency-hop to match a transmit channel of a particular beacon. The quality of synchronization may further be reported to users and/or administrators and may be logged for subsequent examination and analysis. The beacon transmit power may be changed in response to detecting synchronization quality below a threshold, the transmit interval increased (thus increasing the effective power) and the location receivers may further select or reject (or the master unit may filter the reports of) particular beacon transmissions in order to improve synchronization quality.

DSP **34** determines the TOA for the received signal by performing coherent or non-coherent detection. Coherent detection at the message level is preferred if information about the transmitted message and signal is available such as frequency deviation of the signal and content of the message. In

either case, coherent detection is performed at the symbol level by matched filter **32**, providing higher signal to noise ratio (SNR) for the TOA measurement.

Referring now to **Figure 4**, a location finding system in accordance with an embodiment of the present invention is depicted. A master unit **30** is coupled to multiple location receivers **20A-20D** via wireless or wired network connections **31A-D**. Within master unit **30** a network interface **32** provides communication with a processor **34** coupled to a memory **34** in which program instructions for execution by processor **34** are stored. Master unit **30** is generally a server that receives TOA information from location receivers **20A-20D** via wireless or wired network connections **31A-D**. A beacon unit **33** (which may comprise multiple beacons and which may be included within one or more of location units **20A-20D** or master unit **30**) provides a reference transmitter signal at periodic intervals. TOA measurements of the receiver reference transmitter signal are provided by location receivers **20A-20D** to master unit **30**, which computes the deviation between the TDOAs calculated from the reported TOAs and the theoretical TDOAs based on known positions of location receivers **20A-20D**. The deviations over a number of received beacon signals (generally 10-200 in the current sample set) are collected in a statistical database and program that

implements a smoothing filter (e.g., a Kalman filter) that acts on the computed deviations. The Kalman filters provide linear estimators for compensating for the bias and drift of each location receiver **20A-20D** timebase over time. The estimators are used to correct the computed TDOAs for location-finding measurements (virtual synchronization), or alternatively, messages are sent messages from master unit **30** to location receivers **20A-20D** that correct the local timebases and/or system clock in location receivers **20A-20D** as described above (physical synchronization) so that the accuracy of location-finding measurements are improved. A Kalman filter may be implemented for each pair of location receivers, or the network may be organized as in **Figure 1** and described in the associated description, so that only differences between individual location receiver timebases and a primary location receiver for the group to which a location receiver belongs, and timebase deviations between the primary location receivers in the network must be tracked.

Referring now to **Figure 5**, a graphical illustration of the bias and drift estimation of the present invention is shown. Line **TOA1-2** represents a best fit mean-square estimate for TOA differences (TDOA) between two location receivers for a series of transmitted signals. The zero time y-axis intercept point is

an indication of a bias from the ideal TDOA minus the theoretical TDOA as measured by the time zero timebase offset for the current location receiver sample set. The slope of the line is a measure of the drift over time. Drift as indicated on the graph at present time $\mathbf{T_f}$ provides a predictor of the value of the TOA error due to bias and drift at future time $\mathbf{T_f}$ and can also be used to retroactively correct non-calibration TDOA measurements that have already been completed for other wireless devices or for non-beacon messages that have already been received by the location receivers. A measure of synchronization quality can also be made from the spread of the data and used to provide an indication of the accuracy of location finding measurements and adjust parameters such as beacon transmit power and/or channel as mentioned above. A log and/or console report of synchronization quality can be maintained for a user readable indication.

Referring now to **Figure 6**, a method in accordance with an embodiment of the invention is depicted. First, for each beacon signal received by the location receivers, the TOA of the signal at each location receiver is detected (**step 40**). Then, the TOAs are reported to the master unit (**step 41**). After the TOAs reported by the location receivers are collected by the master unit, if a group primary location receiver is not reporting the

beacon TOA (**decision 42**), then a beacon TOA is computed for the physical location of the primary location receiver based on the TOA of the beacon signal received at a secondary location receiver (**step 43**) and the known positions of the primary and secondary location receivers. Once all of the primary location receiver TOAs have been received at the master unit along with all location receiver TOAs from reporting location receivers, then TDOA offsets from each group primary location receiver are computed for each other location receiver in the group (**step 44**). Then, the TDOA offsets are adjusted between the groups using the mutual location receiver pair TDOAs (**step 45**). After the TDOA offsets for all reporting location receivers have been computed, the statistical sets for each of the Kalman filters are updated (**step 46**) and the bias and offset of the location receiver timebases are estimated for each location receiver from the Kalman parameters (**step 47**). Finally the locations of other wireless devices can be determined using estimates of current bias and drift of the individual location receivers' timebases (**step 48**), including the location of the participating location receivers themselves subsequent (or prior in the case of retroactive correction) to the calibration interval. Alternatively in (**step 48**) the correction may be made by tuning the clocks/timebases of the individual location receivers via

network messages as described above, which will provide correction of TDOAs computed from subsequently received TOAs.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in form, and details may be made therein without departing from the spirit and scope of the invention.